[ENE01] Development of power system dynamic equivalents toolbox for digital type power system simulator

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Introduction

The aim of this research is to develop a power system dynamic equivalents toolbox (PSDYNET) for digital type power system simulator. In dynamics study of large power system, it is of the essence to represent the external system by means of dynamic equivalents with the intention of improve the solution speed and to reduce the problem into a solvable size. This is for the reason that detailed representation of large power system is restricted in digital simulation program such as EMTP, PSCAD/EMTDC and TNA. At the present time, TNB is still practicing to use the static equivalents for their system analysis and studies. As a result of this, their off-line simulation studies are presently limited to steady state analysis and electromagnetic transient studies only. PSDYNET has been developed in this research so as to expand the TNB works to transient and electromechanical simulation studies.

Accurate modelling of power system dynamic equivalent model at the boundary points is an important prerequisite for meaningful exploratory studies, analysis and designs of systems those involving power electronic applications such as HVDC transmission, Static VAR Compensators and FACTS. Generally, the power system structures will include internal system (study system) and external system (which is represented by dynamic equivalents system).

Efforts to find appropriate dynamic equivalents have been reported since three decades ago. In the common practice, the external system is normally replaced by one or more coherent groups of synchronous machines (Podmore, 1979). Other methods like modal analysis (Oliveira et al, 1988), energy function (Wang *et al.*, 1997) and rotor angle based coherency analysis (Qi, 1994), etc. has been reported in the literature.

An analytical method is proposed to identify the dynamic equivalents network, i.e. by means of the parametric identification method. The method is based on the line flow function of the original power system. The external system will be reduced and replaced by dynamic equivalent generator models. The active power (P) is afterwards utilises to identify the dynamic equivalent generator parameters such as inertia constant, H, damping factor, D and synchronous and transient reactances (X_d, X_q, X_d', X_q'), etc. The parameters identification process is optimized using the non-linear optimization algorithms such as Levenberg-Marquardt (LM) algorithm.

Towards the end of this research, a flexible and accurate dynamic equivalents toolbox is expected as the whole research output. The toolbox will consists of a range of power system programs such as power flow analysis program, time domain simulation program, and dynamic equivalents identification program.

Methodology and tool

The introducing of dynamic equivalents for large power system basically involves the reducing numbers of differential equations to be solved while preserving the most important dynamic characteristics of the external system. This alternative method introduces the order reduction process of electrical grid system and at the same time, it preserves only the frontier buses. Fictitious generators are then located at the frontier buses to represent the external system. Figure 1 shows the related interactive buses in a power system which is divided into study and external systems.

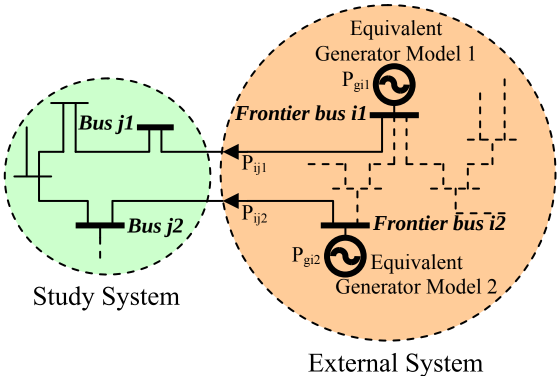

FIGURE 1 The interactive buses in a system.

The main objective of the methodology is to identify the best parameters of the equivalent generators in the reduction order model which are then produce least error in dynamic response as compare to the full order model. An optimization algorithm is utilised together with minimization process in order to attain this matching.

Steady state preservation

The first step in the network order reduction is to verify its steady state preservation. This is done by load flow study. The complex power flow that should be injected into the fictitious generators at the frontier buses is calculated through the load flow analysis. The bus power balancing equation is as follows:

$$\sum_{k\in J} P_{ik} + P_{gi} + P_{li} = 0, \ \forall i \in I \tag{1}$$

where J is the set of buses which linked to the ith frontier bus, I is the set of frontier buses, P_{ik} is the active power flowing from ith bus to kth bus, P_{gi} is the generation active power at the ith bus, P_{li} is the load active power at the ith bus. The voltage level at the frontier buses will be adjusted to the values as calculated in the full order system load flow study.

Dynamic equivalent generator model

Fourth order generator model with excitation system is employed to represent the equivalent generators model located at the frontier buses. The generator model is a two-axis with one field winding in d-axis and one damping winding in q-axis. The differential equations describing the synchronous generator written in its individual d-q rotor reference frame is expressed as follows (Galarza, 1996):

$$\frac{d\delta_i}{dt} = \omega_i - \omega_0 \tag{2}$$

$$\frac{d\omega_i}{dt} = \frac{1}{M_i}[P_{mi} - (E'_{qi} - X'_{di} I_{di}) I_{qi} - (E'_{di} + X'_{qi} I_{qi}) I_{di} - D_i(\omega_i - \omega_0)] \tag{3}$$

$$\frac{dE'_{qi}}{dt} = \frac{1}{T'_{d0i}}[E_{fdi} - (X_{di} - X'_{di}) I_{di} - E'_{qi}] \tag{4}$$

$$\frac{dE'_{di}}{dt} = \frac{1}{T'_{q0i}}[-E'_{di} + (X_{qi} - X'_{qi}) I_{qi}] \tag{5}$$

where $M_i = \dfrac{2H_i S_{ni}}{\omega_{Si}}$, S_{ni} is the machine MVA rating, δ is machine rotor angle, ω_{Si} is machine synchronous speed, P_m is machine mechanical power, E'_d and E'_q are d-axis and q-axis voltages respectively, X and X' are synchronous and transient reactances respectively, T is time constant in second, E_f is exciter field voltage, and H is the machine inertia. Equations (2) and (3) describe the rotor mechanical dynamics in the state variables δ and ω, while (4) and (5) represent the rotor electrical equations in the state variables E'_d and E'_q. The machine model also involves algebraic equations for the stator transformed into the complex network reference frame and is written as follows:

$$E'_{di} - V_{Ti}\sin(\delta_i - \theta_i) - I_{di} R_{Si} + I_{qi} X'_{qi} = 0 \tag{6}$$

$$E'_{qi} - V_{Ti}\cos(\delta_i - \theta_i) - I_{qi} R_{Si} + I_{di} X'_{di} = 0 \tag{7}$$

Algorithm of parameters identification

The parameters identification will be done in time domain. The tuning of the parameters of equivalent generators is done so as to match the full model time response output. The objective of the time domain identification is, for the time interval $t = 0$ to $t = T_0$, to fit the parameter, x to minimize the error function (Stankovic, 2003),

$$J_T(x) = \int_0^{T_0} (y_r(t) - y_{fm}(t))^T (y_r(t) - y_{fm}(t))dt \tag{8}$$

where $y_r(t)$ and $y_{fm}(t)$ are the output of the reduced and full models, respectively.

Minimization of the squared difference of active power flows at the frontier lines is utilised for the identification. This condition is express as:

$$\min J(x),$$

$$\sum_{i\in I}\sum_{k\in K}(P_{ik}^{o} - f_{ik}(x))^2 = \sum_{i\in I}\sum_{k\in K}(P_{ik}^{o} - P_{ik}^{eq})^2 \qquad (9)$$

where K is the set of buses in the study system linked with frontier buses, x is the vector of parameters to be identified, P_{ik}^{o} is the active power flow from ith to kth bus in the full order system, $f_{ik}(x) = P_{ik}^{eq}$ is the active power flow from ith to kth bus in the equivalent system.

The flow chart of the overview methodology is depicted in Figure 2. The frontier buses are those buses of the external system which are linking with the studied system.

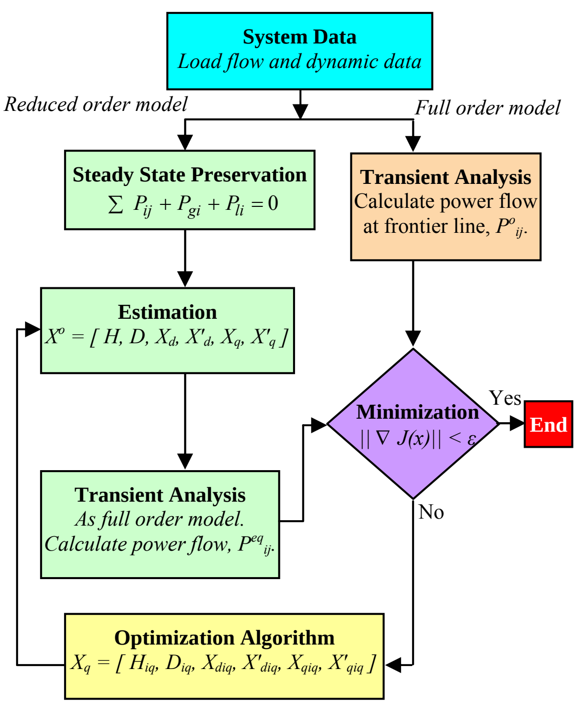

FIGURE 2 The flow diagram of parameters identification technique.

The objective function of the optimization problem solved by the Levenberg-Marquardt (LM) Algorithm can be expressed as (More,1977):

$$J(x) = [r(x)]^T [r(x)] \qquad (10)$$

where $r(x) = P^{o} - f(x)$ (11)

is the criterion function.

The minimize of *J(x)* can be achieved by differentiate equation (10) and equate to zero, $\hat{x}$ must satisfy the nonlinear equation,

$$\left.\frac{dJ(x)}{dx}\right|_{x=\hat{x}} = -2[F(\hat{x})]^T [P^{o} - f(\hat{x})] = 0 \qquad (12)$$

where $F(\hat{x}) = \left. {df(x)}/{dx} \right|_{x=\hat{x}}$ is Jacobian matrix.

One of the methods to solve the equation (12) is based on Taylor series approximation of *f(x)* around a nominal point, x^{o},

$$f(x) = f(x^{o}) + F(x^{o})[\hat{x} - x^{o}] \qquad (13)$$

Substituting equation (13) into equation (12) yields,

$$[F^T(x^{o})F(x^{o})][\hat{x} - x^{o}] = F^T(x^{o})[P^{o} - f(x^{o})] \qquad (14)$$

$$[F^T(x^{q})F(x^{q})]\Delta x^{q+1} = F^T(x^{q})r(x^{q}) \qquad (15)$$

Solve iteratively $x^{q+1} + x^{q} + \Delta x^{q+1}$, where $r(x^{q}) = P^{o}\text{-}f(x^{q})$ is the residual in qth iteration. The iterations of equations (14) and (15) are continued until $J(\hat{x})$ approaches a minimum value. According to Levenberg-Marquardt Algorithm (More, 1977), equations (14) and (15) may be solved by adding a positive number to the diagonal of the matrix $F(x^{q})^T F(x^{q})$ for fear that of oscillatory behaviour in convergence and/or ill-conditioning of the matrix. So, equation (15) becomes,

$$[F^T(x^{q})F(x^{q}) + \alpha D]\Delta x^{q+1} = F^T(x^{q})r(x^{q}) \qquad (16)$$

where D is a diagonal matrix and the constant $\alpha > 0$.

Toolbox – PSDYNET program

The Graphic User Interface *(GUI)* layout for the Power System Dynamic Equivalents Toolbox (*PSDYNET)* is shown in Figure 3. It has been developed in Matlab environment for the purpose of constructing the power system dynamic equivalents network. Principally, it consists of three major programs – power flow analysis program, time domain simulations program, and dynamic equivalent identification program. Other utility tools that available with *PSDYNET* are static report generation (for power flow) and plotting page (for time domain simulations).

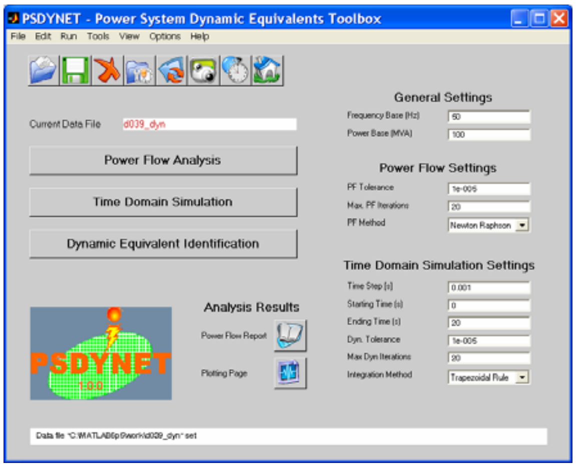

FIGURE 3 The layout of PSDYNET program.

Simulation results and discussion

Test system model

For the purpose of evaluating the method developed in this paper for dynamic equivalents identification, a detailed 39-bus IEEE system containing 10 generator units and 46 lines is used. This system represents the New England area 345-kV bulk transmission network. Machine 10 at bus 39 is an equivalent power source representing parts of the U.S.-Canadian interconnection system. Machine 2 is chosen as a reference (slack bus) for the other nine machines. A one-line diagram of the system is depicted in Figure 4. The system is separated into a study system and an external system as shown. The study system contains generating units 2 and 3 while the other generating units are belongs to the external system. Thus, there are three frontier buses (3, 15, and 39) and three frontier lines (3-4, 15-14, and 39-9). Figure 5 shows an equivalent network including three fictitious generating units and equivalent loads at bus 3, 15, and 39. The evaluation procedure is performed by applying a three-phase fault on bus 4 at simulation time, $t = 2.0$ and clearing the fault by removing it at $t = 2.1$.

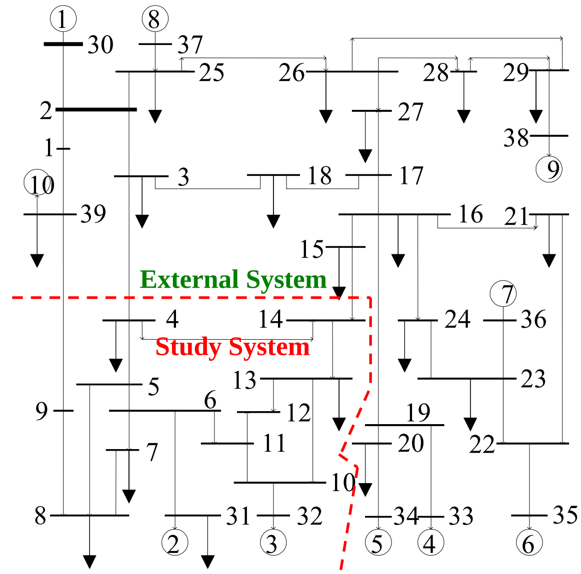

FIGURE 4 The 39-bus New England system.

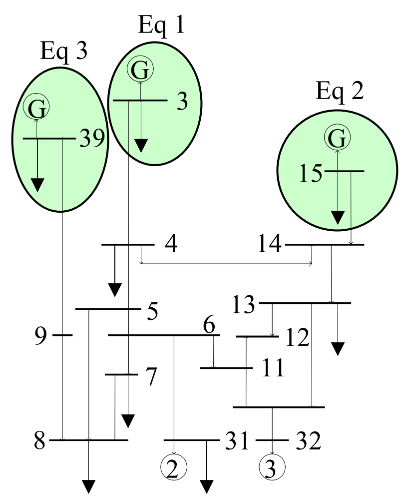

FIGURE 5 The equivalent network.

Results and discussion

Table 1 exhibits the estimated parameters for the fictitious generating units, under the consideration aforementioned (LM algorithm).

TABLE 1 The estimated equivalent parameters.

Gen	X_d	X'_d	T'_{do}	X_q	X'_q	T'_{qo}	H	D
Eq1	0.371	0.128	7.5	0.344	0.141	1.67	6.7	0
Eq2	0.369	0.112	7.6	0.339	0.184	1.73	6.3	0
Eq3	0.392	0.136	7.9	0.355	0.132	1.84	7.6	0

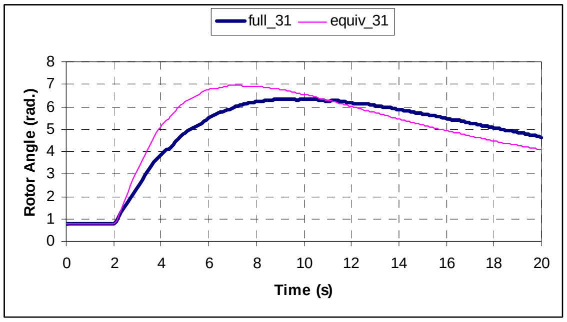

FIGURE 6 Rotor angle of machine 31.

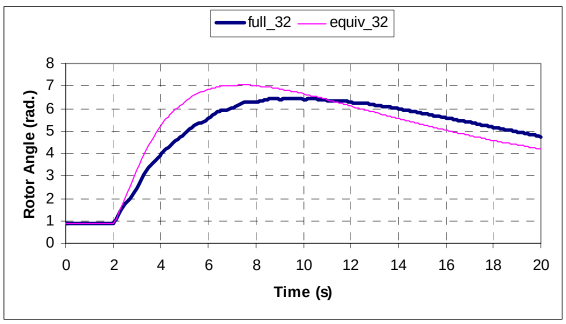

FIGURE 7 Rotor angle (δ) of machine 32.

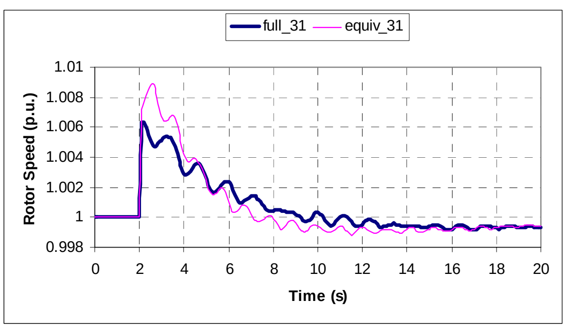

FIGURE 8 Rotor speed (ω) of machine 31.

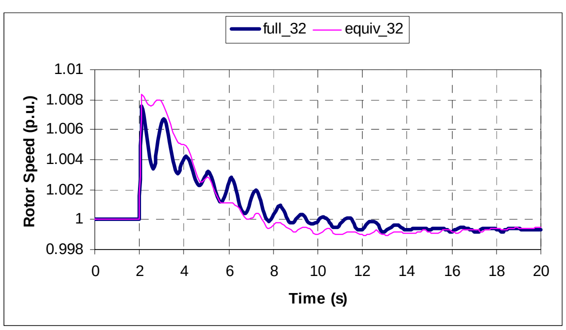

FIGURE 9 Rotor speed (ω) of machine 32.

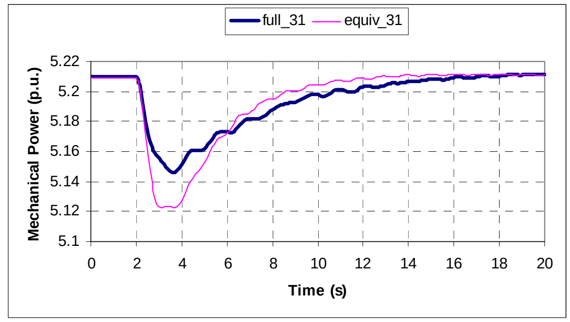

FIGURE 10 Mechanical power of machine 31.

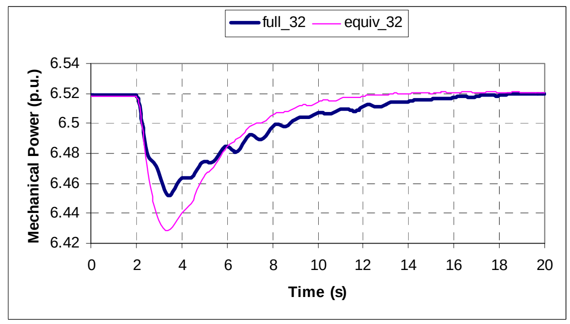

FIGURE 11 Mechanical power of machine 32.

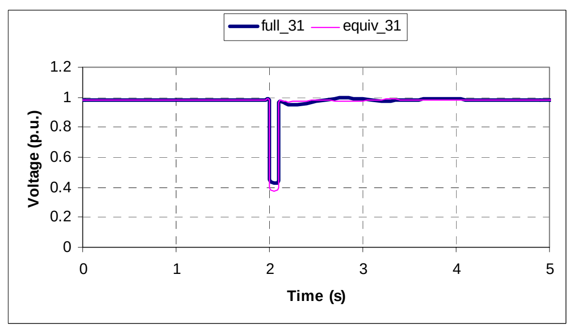

FIGURE 12 Voltage at generator bus 31.

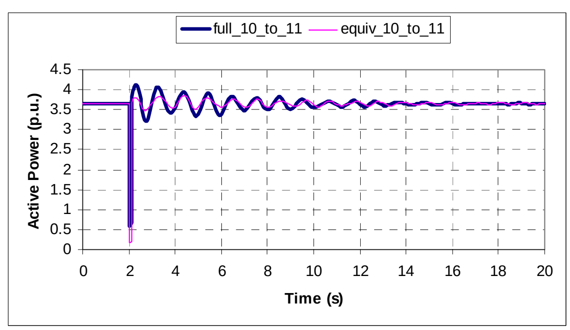

FIGURE 13 Active power flows at the line 10-11.

The quality of the estimation was confirmed by transient stability study. Figures 6 to 13 depict the sample of the corresponding dynamic responses, comparing the behaviour of the full and reduced system after the three-phase fault. It is observed from the simulation results that the plotted dynamic behaviours are satisfactorily close to the original full system. Besides simplified the system modelling works, another main benefit that can be gained from the reduction process is to save the CPU run time. Table 2 gives the overall simulation performance of both the full and the reduced system which are running on PC platform with Pentium IV, 2.0 GHz processor and 256MB RAM.

TABLE 2 CPU run time for power flow analysis and time domain simulation

Analysis	Time in sec. (Full)	Time in sec. (Reduced)
Power flow	0.341	0.180
Time domain simulation	19.339	12.688

Conclusions

The formulation of a new alternative methodology is proposed to obtain the power system dynamic equivalents which preserve satisfactorily the set of electromechanical modes associated to generators of the studied system. External system is replaced with fictitious generating units and its equivalent loads whose consequent parameters are included in the solution. Such formulation is posed as non-linear optimization problem that can be solved by a range of methods. In this paper, the Levenberg-Marquardt algorithm has been selected to solve the problem due to its robustness in convergence matter. For further study the problem, biological inspired algorithm such as Genetic Algorithm (GA) and social behavior inspired algorithm such as Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) are suggested for the parameter identification procedures.

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